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AGARD ADVISORY REPORT No. 173

Technical Evaluation Report on the Fluid Dynamics Panel Symposium on Aerodynamics of Power Plant Installation

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ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

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AGARD Advisory Report No.173

TECHNICAL EVALUATION REPORT

on the

FLUID DYNAMICS PANEL SYMPOSIUM

on

AERODYNAMICS OF POWER PLANT INSTALLATION

by

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This Advisory Report was produced at the request of the Fluid Dynamics Panel of AGARD.

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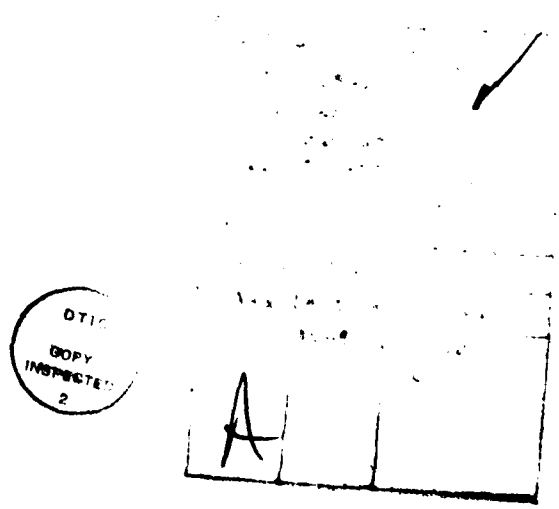
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A TECHNICAL EVALUATION REPORT FOR THE SYMPOSIUM ON "AERODYNAMICS OF POWER PLANT INSTALLATION" (TOULOUSE, FRANCE, 11-14 MAY 1981)

by

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1. INTRODUCTION

The AGARD Fluid Dynamics Panel held its spring symposium 1981 on the "Aerodynamics of Power Plant Installation," at the Ecole Nationale Supericure de L' Aeronautique et de L' Espace, complexe Aerospatiel de Lespinte, Toulouse France, 11-14 May 1981. The symposium was prepared by a program committee whose members were: Dr. J. E. Green (co-chairman), A. Coursimault, Dr. K. Gersten, Dr. G. K. Richey, Dr. U. Sacerdote, Dr. J. Dunham (co-chairman), H. I. Bush, Prof. Dr. Dini, and Dr. D. K. Hennecke. The theme of the symposium was as indicated in the announcement:

> Powerplant installations involve complex flows, strongly influenced by viscous effects and often with important aerodynamic interactions between the airframe and propulsion system. The introduction of new vehicle propulsion concepts, and new points of emphasis in aircraft and missile design requirements, provide an expanding range of aerodynamic problems which call for both experimental and theoretical study. It is the purpose of the symposium to survey the current and foreseeable aerodynamic problems in powerplant installation and to review recent work which has improved basic understanding or has enhanced prediction and design methods in this field.

Within this context, the symposium focused on powerplant installation effects for both combat and transport aircraft. Four sessions were planned with a total of 34 papers presented. These sessions were:

I - Combat aircraft intakes

II - Afterbodies and nozzles

III - Testing and analysis techniques

IV - Installation aerodynamics of transport aircraft

The symposium concluded with a round tabel discussion, in which the current status of the technology and the areas requiring further consideration was presented.

2. The Sessions

2.1 Combat Aircraft Intakes

This first session focused on the following four areas of research for inlets:

High angle of attack effects (3, 5, 6)

Developments on operational aircraft (9, 10)

Developments of theoretical methods (4, 7, 8)

Advanced concepts (1, 2)

Aircraft of the future will be required to operate over an expanded operational envelope. Extending this envelope and increasing the maneuverability within this envelope will present the aircraft designer with many unusual challenges. Considerable research will be required in order to assure the compatibility of the intake with the engine. In the past, the research in this area has primarily been experimental in nature leading to lengthy wind tunnel developmental programs. The development of theoretical methods has the potential for minimizing the development time and cost. Future concepts will not only have to operate over an expanded flight envelope, but must do so with reduced detectability. These requirements may dictate some rather unusual configurational concepts requiring careful research, both experimental and theoretical, in order for the inlet/engine system not to adversely effect the performance of the aircraft. This first session will carefully address those areas illustrating the state of the art in aircraft intakes.

Expanding the flight envelope affects many aspects of aircraft design, including those of the propulsion system. Inlet performance may well be crucial under these conditions. It is, therefore, imperative that a high level of pressure recovery be maintained, as well as the total pressure distortion and turbulence be kept below specified levels. In the paper prepared by J. A. Ross, I. McGregor, and A. J. Priest (3) research aimed at improving the angle-of-attack performance of fuselage mounted intakes was summarized. Simple changes such as; lip shaping, inlet shielding, and lip stagger were shown to be effective in improving the subsonic performance. Such modifications, however, incur significant supersonic drag penalties. The inlet performance and distortion characteristics are highly configuration dependent as evidenced by the inlet-strake interactions illustrated in this paper. A fairly short, broad strake gave the lowest distortion levels. These results are contridictory to the strake geometry required for good high angle of attack vortex lift development. Careful consideration of geometric variables and

their interaction effects will be required in any future aircraft design. The paper prepared by A. C. Williams, T. W. Brown, and E. L. Goldsmith (5) extends previous research aimed at studying the sensitivity of intake performance and compatibility to detailed lip design and diffuser geometry at high angles of attack, including an assessment of the effects of duct offset on flow distortion. These results show, as you would expect, that distortion levels can be set by the diffuser as much as by angle of attack. In the paper prepared by A. Dyment, P. Gryson, and J. P. Flodrops (6) flow visualization photos of an air intake operating at angles of attack of 20^{o} and 40^{o} are presented. These data illustrate the flow separation that occurs and show that auxiliary devices such as slots or scoops are effective in improving the inlet performance. The problems illustrated in these papers are very difficult to analyze. While the development of theoretical methods, which can aid in attacking this problem is underway, experimental programs will be the primary tool used in aircraft development programs. For example, in the paper prepared by R. C. Kemper, methods of converting a single engine inlet system to a twin engine configuration are discussed. The effects of various duct bifurcations on the performance and surge characteristics were studied. The results indicated that with modifications such as a splitter between the engines, the surge crosstalk can be reduced. However, it is felt that for an engine out case due to engine failure, engine parts could travel upstream and seriously damage the second engine. It would appear that an increased level of research would be required before this concept would be considered for application. In the paper prepared by C. P. Stokes, and N. C. Bissinger (10) the design and development of the air intake for the tornado aircraft was discussed. The data of this paper describes a cowl flow separation problem which occurred at an angle of attack of 20^{o} and pointed out that cambering and blunting the lower cowl lip significantly reduced the distortion. As you would expect, blunting the cowl lip while improving the flow characteristics will result in a small penalty in supersonic drag. One of the most significant points made in this paper is that the flow field induced by the inlets exerts a significant influence on the overall aircraft aerodynamics. As a result, continuous contact between the airframe and engine manufacturers must be maintained and propulsion integration testing must be conducted at the earliest possible time such that potential problems can be resolved.

In the past, aircraft developmental programs have relied on extensive use of experimental facilities to develop new aircraft concepts. This approach has led to extremely long and costly wind tunnel developmental programs and generally also results in extensive wind tunnel fix-it programs. Considerable effort is being devoted to the development of computational methods, which have the potential for minimizing the use of these experimental facilitites. The wind tunnel facilities can then be utilized to validate the configurational concepts or to explore new areas where theoretical methods can not provide an adequate solution. In the paper prepared by D. E. Colbourne, and J. E. Flitcroft (4) a computational method for predicting the three-dimensional flows within the diffuser sections is described. The primary consideration was the development of a novel, fast method for automatic grid-generation applicable to ducts of any smoothly varying cross-sectional shape. This method is based on an analytical solution to the Laplace equation.requiring no user intervention to modify the generated grid, and only 12 to 24 seconds computing time per plane. This research is significant in that grid generation methods are one of the keys to the development of efficient and accurate computational methods. A very important consideration is that any new code must be developed with the user in mind, such that the complexity is handled by the computer and not the user.

In the paper prepared by C. W. Lucchi (7) a method for predicting the transonic flow about aircraft intakes is described. This procedure started with simple 2-D airfoil theory and is building toward development of a method for predicting the 3-D flow effects. A finite -element method was used to solve the full potential flow equation for transonic flows. The results compared relatively well with the experimental results, however, a considerable amount of research is required before a fully dependable code is developed that can handle 3-D flows at the higher angles of attack, particularly when flow separation effects occur. One of the key areas for future research is to develop methods for reducing computational time. Unless these new codes, particularly 3-D flow methods, can yield solutions in a reasonable amount of time, they will not be fully utilized.

In the paper prepared by G. Bertolone, and L. Fornasier (8) a method for evaluating air intake performance is discussed. This paper, like that of paper No. 7, discussed methods based on the modifications of existing codes that suitable for computing the flow past two dimensional airfoils, and about three-dimensional bodies (panel methods). These methods can be useful in predicting the flow characteristics at low angles of attack. However, it will take a more rigorous method to predict the flow at off-design conditions.

Requirements for future tactical aircraft will force designers to consider a broader range of configuration variables. For example, improved Mach number capability coupled with STOL capability, all at a reduced level of detectability could force designers to consider inlet and diffuser geometries which are significantly different from those incorporated into today's fighter aircraft. Papers numbers 1 and 2 discuss several of these new concepts. In the paper prepared by L. Surber, J. Syberg, and J. Koncsek, (..) the performance of highly integrated inlets for supersonic cruise aircraft was discussed. Three diffusers were designed for inlets having throat aspect ratios greater than seven and a fourth designed for a low aspect ratio. Two of the high aspect ratio and the low aspect ratio diffuser incorporated duct bends typical of inlets substantially off-set from the engine center line. The results indicate that reasonably high supersonic inlet performance can be achieved in high aspect ratio two-dimensional inlets and that pressure recovery penalties associated with long, highly curved diffusers can be small in a properly designed and integrated inlet. The results indicate the usefulness of analytical methods, even a simple method (one-dimensional boundary layer method) in designing highly curved ducts. New and more rigorous methods have been and are under development which can be utilized to give a more accurate definition of the flow in these ducts. Future programs should be structured to take full advantage of these new methods.

In the paper prepared by T. L. Williams, B. L. Hunt, and D. B. Smeltzer, and W. P. Nelms (2), the feasibility of top-mounted inlets for tactical aircraft application was discussed. This type of inlet arrangement is seen to provide a variety of potential advantages, including improved weapons integration, reduced structural weight, elimination of hot gas reingestion, and reduced fronted aspect radar cross-section. It is expected, however, that this inlet location would suffer from performance problems, particularly at off-design conditions. The results from this paper indicate that with careful attention

to design principles (utilization of vortex flows to keep low energy boundary layers from entering inlets) relatively good inlet performance and compatibility characteristics can be maintained during subsonic and transonic maneuvers. However, at supersonic speeds flow expansion over the forebody and wings causes an increase in the local velocities at the inlet, which naturally reduces inlet performance.

2.2 Afterbodies and nozzles

The second session of this conference focused on three major topics:

Nozzle concepts for current tactical aircraft (12, 13)

Reynolds number effects on afterbody drag (16)

Advanced nozzle concepts (11, 14, 15)

In the paper prepared by L. R. Harper (12) the performance consideration involved in the solution of a variable area nozzle for a reheated turbofan engine were discussed. The main emphasis was on dry power operation at subsonic speeds since drag, weight, blockage, etc. can prevent an aircraft from attaining its design mission radius. A variety of nozzle types were considered such as a moving flap, iris, balanced beam, and moving nozzles each varying in complexity, weight and geometric shape. The author illustrated that the moving shroud nozzle, because of its light weight and simplicity, is the preferred choice for the aircraft under consideration (that is a Tornado). This solution is obvious for aircraft which are designed for predominantly subsonic operation. If however, efficient multi-mission capability is required, which includes supersonic capability, then other types of nozzles will undoubtly be superior. The drag data utilized to assist in the nozzle selection is based on empirical correlations of drag as a function of boattail angle. While this type of data may yield trends in the variation of drag, the relative levels of drag for one type of nozzle versus another may be misleading, particularly since the experiment used in the correlation is seldom on configurations under study. It should also be pointed out that these data are for isolated nozzles and the results can be significantly altered once they are integrated into an aircraft configuration.

In the paper prepared by H. Grieb, R. Vedova, H. Endarle, and H. Nagel (13) the advantages and disadvantages of the various nozzle concepts were pointed out. The conclusion drawn from this discussion is that the choice between the more complex convergent-divergent nozzles and the simple short-flap nozzle must be based on the mission requirements of the aircraft concept.

The ability to predict the full scale afterbody drag for tactical aircraft from wind tunnel data has aroused considerable concern within the aeronautical community, particularly since several research programs indicated unpredictable trends of drag as a function of Reynolds number. In the paper prepared by O. M. Pozniak (16) a review of the effects of Reynolds number on afterbody drag was presented. The results of this study were essentially the same as those found in NASA-Langley Research Center studies, that is significant but compensating pressure changes occur on the nozzle/afterbody, but little effect on the total afterbody pressure drag is noted. The studies made to date have been somewhat limited, because of the limited Reynolds number capability or the size of the available facilities. Facilities currently under construction such as the National Aeronautics and Space Administration's National Transonic Facility (cryogenic tunnel) will be able to simulate the range of Reynolds number up to full scale flight conditions, which should be able to fully answer this recurring question.

The requirements for future aircraft may be somewhat different from those of current operational tactical aircraft. For example, nozzle development for the current aircraft has been oriented toward improved cruise performance. For future aircraft, operational considerations have generated an interest in short take-off and landing capability which may be provided by vectoring and reversing nozzles. It is evident that increased operational capability will be required in these aircraft, and that the propulsion may be utilized to provide this capability. In the paper prepared by D. L. Bowers and J. A. Laughrey (11) the integration of advanced exhaust nozzles was discussed. It was pointed out that the potential for significant aircraft performance improvement lies in the proper utilization of advanced exhaust nozzle technology in concert with other emerging aircraft technologies. Advanced nozzle concepts can provide cruise drag reductions especially when used as a trimming device, STOL capability and enhanced maneuverability through the use of thrust vectoring and reversing. One of the nozzle concepts which lends itself to these enhanced mission requirements is the nonaxisymmetric nozzle. This concept appears to be lighter than other nozzles if thrust vectoring and reversing is included. When research on this nozzle concept was first initiated it was felt that the primary problems would be low internal performance, high weight and increased cooling flow requirements. However, as pointed out in the paper prepared by R. J. Glidewell and R. E. Worbuton (14) these areas of concern did not appear to be a problem. For example, the nonaxisymmetric nozzle requires less cooling flow than the axisymmetric nozzle since this nozzle lends itself to the use of more efficient cooling schemes. In experimental studies the nonaxisymmetric nozzles have demonstrated as high, if not slightly higher internal performance that the axisymmetric nozzles. It is also shown in this paper that nonaxisymmetric nozzles may offer some weight advantage if multifunctions such as vectoring and reversing are required. It is obvious that nonaxisymmetric nozzles are competitive with axisymmetric nozzles and may indeed be better suited, based on future tactical aircraft requirements, for incorporation into future fighter aircraft.

This interest in nonaxisymmetric nozzles has generated many research programs on various types of nozzle concepts. One such nozzle concept, a single expansion ramp nozzle, has undergone extensive experimental testing, as pointed out in the paper prepared by K. M. Peery and D. L. Russell (15). The SERN test data revealed that a significant variation in nozzle flow field characteristics occurred as the exhaust total temperature was changed. In this study a two-dimensional Navier-Stokes flow analysis was used to simulate the SERN flow field in an attempt to understand the observed effects. The results of the analysis did not predict these temperature effects, primarily because the method failed to predict the presence of a normal shock on the expansion ramp. The internal shape of the nozzle used in this study was very three-dimensional, and it would be expected that the 2-D theory would be inadequate to predict the details of the flow. There are methods available which can predict the 3-D flow characteristics and

one of these should be utilized to determine if the observed flow characteristics can be predicted.

2.3 Testing and Analysis Techniques

This third session focuses on three main topics:

Inlet Flow Simulation and Analysis (17-20)

Analysis of Flight Problems (21)

Propulsion Simulation for Transport Aircraft (22-26)

This area of research is one of the most complicated, time consuming and difficult areas encountered during the research and development process. In general there is a need for vast amounts of high quality data particularly since 1 or 2 drag counts are critical to the design of some aircraft concepts. The primary problem then becomes how best to simulate the propulsion system such that the desired accuracy can be obtained. In addition analyzing the large volume of data is very expensive and may not be appropriate in the early stages of a design cycle. As a result methods for analyzing large volumes of data rapidly and methods of selectively obtaining data which will reflect the performance parameters under study is extremely important. In this session, current methods utilized in industry will be discussed as well as several novel approaches to propulsion system simulations.

Since fighter aircraft will operate over a large angle of attack range extensive inlet-engine compatibility analysis will be required. In the paper prepared by B. Delahaye and G. Laruelle (17) a method for simulating the flow that would be present at the engine compressor face at high angle of attack in a static test facility is discussed. This is a novel approach using bell-mouthed inlets having varying lip thickness and bevel-edged ducts to simulate the large vortices generated in an inlet at high angles of attack. This approach appears to be an effective tool in simulating inlet distortion, however it would appear that the unsteady effects would not be simulated. The large volume of data required for an accurate assessment of the distortion effects can be enormous. It is necessary as pointed out in the paper prepared by P. Perrier, B. Delahaye, and G. Laruelle (18) to define a system whereby selected data would eliminate the need for obtaining the usual large volume of data. In the system the authors conclude that 64 unsteady channels of data would be required to provide an adequate distribution of the flow at the compressor face. This same problem is pointed out in the paper prepared by R. Borg (19) where the requirement for maximum instantaneous inlet distortion measurements has significantly increased the cost of testing and analyzing data. For screening purposes there is a need for a simple method for estimating maximum instantaneous distortion. The method suggested is based on time averaged values such as steady state RMS inlet rake pressures using small scale models having relatively sparse instrumentation. These data are combined to an artificial instantaneous distortion pattern using a random number generator and a distortion index is then chosen and evaluated. The results indicated an accuracy level of ±20 percent. This accuracy may be sufficient for screening purposes but for a development program it would be inadequate.

In the paper prepared by J. S. Holdhusen and J. L. Grummel (20) two methods of measuring inlet drag in transonic flow were described. The first method uses a flow through nacelle with a correction applied for the drag force exerted by the capture streamtube on the rest of the nacelle as determined from blown nacelle test in a static test facility. In the second method the drag is determined directly from a single test using a rig which has a variable-loss throttle. In measurements of this type a high level of accuracy is difficult to obtain, since the drag levels are generally small. For this reason it is felt that the second method, since it utilizes only one discrete test, would be the best method to use. Anytime more that one test setup is required then problems in maintaining a high level of accuracy becomes more evident.

In any aircraft development program there is a conflict which always arises between the amount of data required and the cost and time associated with obtaining this data. In many cases schedules are important and the time is not available to fully investigate every facet of the aircraft. For these reasons the flight test activity is considered very important and should be used to investigate the many unforeseen problems which inevitably arise. In the paper prepared by W. L. Macmillan, D. M. Rudnitski and W. Grabe (21) the need for flight test activities is effectively illustrated. This paper discussed a program aimed at investigating a compressor stall problem which occurred on the CF-5 aircraft. The studies indicated that the major cause of the compressor stalls was an improper operation of the engines control system at low temperature conditions. It is an obvious conclusion that conducting extensive ground based and flight tests with properly instrumented aircraft can identify, correct and hopefully avoid this type of problem in future aircraft designs.

Research and development work on future transport aircraft demands a reliable assessment of the engine interference effects in order to fully exploit the performance potential of the aircraft. The determination of the propulsion system interference drag is one of the major tasks confronting an aircraft designer. The main problem is the simulation and calibration of the propulsion simulation system. The various simulation systems that have been utilized are flow-through powered (blown) ejectors or turbine powered nacelles. In papers numbered 22 through 25, these methods were discussed.

In the paper prepared by B. Ewald and R. Smyth (22) the advantages and disadvantages of each of these propulsion simulation systems was discussed. The flow through nacelles which provide the simplest method of propulsion system simulation simulate the inlet flow but not the jet exhaust flow. The blown nacelles have a faired intake (no inlet flow simulation) and a jet exhaust flow simulated by high pressure air. The ejector nacelle represents a partial simulation of the intake flow but the exhaust flow has extreme mixing turbulence which is characteristic of ejectors. The turbine powered simulators come closest to simulating the proper flow conditions, however the intake mass flow in relation to the real engine is reduced by the gas generator part of the total massflow. This can be corrected by modifying the inlet

lip contours. In summary, there is no exact method for simulating the propulsion system for small scale model testing, however the turbine powered simulator (TPS) comes the closest. The primary disadvantage of the TPS is its complexity, requiring extensive calibrations of the system. It would appear that because of the complexity of the TPS system that they would not be used for every test, but would be used during final development when accurate drag measurements are required. For preliminary design studies other simulation systems such as flow-through or blown nacelles would be more appropriate. This line of thought is also presented in the paper prepared by J. P. Becle and R. Perin (23) and in the paper prepared by A. E. Harris and E. C. Carter (24). In addition, in the paper by Harris and Carter (24) a discussion of whether to test with a half span model or a full span model is presented. It was pointed out that a half span model will not yield absolute drag levels, but can only be used to provide incremental drag changes, where model modifications are confined to the nacelle/pylon/wing area. If the nacelle installation interferes with the fuselage flow field or if the total drag is required then a full span model would be required.

Validation of a propulsion simulation method was carried one step further in the paper prepared by G. Pugh and A. E. Harris (25) in that flight data was utilized to verify the turbine powered simulation method. The results from the model to flight correlation appeared to be reasonably good at most flight conditions, however this could be fortuitous since the accuracy of flight data in general is not as good as for wind tunnel data.

Another approach to propulsion integration wind tunnel testing is illustrated in the paper prepared by J. A. J. Van Engelen, B. Munniksma and A. Elsenaar (26). In this paper an evaluation of an experimental technique used to investigate the effects of engine position on engine/pylon/wing interference is presented. In the early stages of aircraft development before the location of the engine is known, the designer would like to develop the parametric data necessary to select the proper location. Moving the nacelle around on the model can be extremely costly and complicated (air and instrumentation lines would need to be relocated). The method expressed in this paper uses both flow through and blown nacelles. The flow through nacelles can be mounted on the model and the blown nacelles mounted on an auxiliary strut support system (not attached to the model). The direct effects are determined from the flow through nacelle test (nacelles mounted directly to the model) and the jet exhaust interference effects from the blown nacelle test (nacelle mounted on alternate strut). Introducing this additional strut into the testing undoubtly causes interference effects which would be difficult to estimate and further complicates the experimental test. It is felt that the data obtained, particularly the flow-through nacelle data can be relied upon to aid in the selection of the engine location.

An additional paper prepared by J. Leynaert (27) which was actually included in the fourth session of this conference, but will be discussed in conjunction with the third session, discusses the need for high Reynolds number testing, particularly for inlet configurations. The paper presents several techniques and facilities in which this type of data could be obtained. It is recognized throughout the aeronautical community that an inadequate Reynolds number simulation is a serious deficiency in aerodynamic testing. The type of facilities presented in this paper, as well as the new cryogenic wind tunnel facilities should be able to adequately address this problem.

2.4 Installation Aerodynamics of Transport Aircraft

The fourth session of this conference focuses on the development of methods for predicting the propulsion interaction effects for transport aircraft. Three classes of transport aircraft are considered in this discussion. These are:

Turbofan installation for subsonic transports

- Fuselage-mounted engines (28, 29)
- Wing-mounted engines (30-32)

Turboprop transports (33)

Supersonic cruise transports (35)

For many jet aircraft, particularly for small business jets, a rear fuselage-mounted engine location is favored. In this position the inlet and exhaust flows not only affect the fuselage/pylons but can, because of close proximity affect the wing flow field. In the paper prepared by R. D. Laugher (28) the influence of close-coupled, fuselage-mounted nacelles on the design on an advanced wing is discussed. The primary methods utilized in the design process were based on subcritical flow analysis, which as shown by the data presented resulted in a reasonably good agreement with experimental data. However, in most cases there are extensive areas of mixed flow on the configuration, and there is at present no method to adequately model the nacelle flow field effects at transonic speeds. This paper recognizes this modeling problem and attempts to simulate the interference effects by replacing the nacelle with a body located co-axially with the nacelle having its nose located in the vicinity of the wing trailing edge. While this approach seems to give good results the concern should be expressed that without experimental data to guide the calculations it would be very difficult to know if the modeling is reasonable. A more reasonable approach is described in the paper prepared by N. Voogt, J. Van Hengst, and J. Th. v.d. Kolk (29). In this paper panel methods were used in a design-by-analysis process. The jet exhaust was represented by a cylinder with zero normal velocities and the inlet flow is modeled by specifying a desired normal velocity distribution in a control plane inside the duct. This approach yields good results, however, it is only good for potential flow and breaks down when regions having strong viscous interactions are present.

In the paper prepared by G. LeGall, J. Bousquet, and M. Yermia (30) a method for predicting the flow characteristics for wing-mounted nacelles is described. The calculation is based on the use of panel methods and is inviscid and incompressible. The inlet flow is represented by the inlet mass

flow and there is no mixing in the jet exhaust flow. As stated previously these methods give good results as long as supersonic bubbles or flow separation does not appear in the flow. It is also obvious that there is a lack of high quality experimental data (flow field and surface pressures) which can be utilized in verifying new computational methods or in developing an understanding of the flow interactions. Satisfying this need should receive a high priority within the aeronautical community. The paper prepared by K. D. Klevenhusen, H. Jacob, and H. Struck (31) combines the panel methods discussed in the previous paper with a finite difference method in order to calculate the wing-body-nacelle interference effects. This procedure basically makes a 3-D calculation for the desired wing and then finds an analogous airfoil section which would yield this pressure distribution. A transonic flow calculation is then made on the analogous section in an attempt to consider 3-D interference effects using a 2-D program. The method appears to be a useful interim approach, however it is felt that it will require development of a 3-D nonlinear potential flow code for wing/body/pylon/nacelles before any accurate solutions are obtained. These procedures are carried a step further in the paper prepared by D. W. Roberts (32) where a numerical procedure was developed to calculate the flow fields resulting from the viscous-inviscid interactions that occur when a strong jet exhaust interacts with an aircraft flow field. The approach in this paper divides the interaction regions into three zones which are either predominately viscous or inviscid. The flow in the inviscid zone is calculated using a potential flow code and in the viscous flow zone, which encompasses the jet exhaust plume, a parabolized Navier-Stokes code. This appraoch is an effective way to treat the various types of flow to be encoutnered for turbofan transport configurations. It would be virtually impossible, because of computational time, to calculate the flow over a complete configuration using the Navier-Stokes equations and the potential flow equation cannot adequately model all the flows encountered. It would naturally seem reasonable that some method of patching solutions together would be the most appropriate method for attacking this complex problem. The primary consideration in an appraoch of this kind is to make certain that the proper boundary conditions are generated and that the interferences generated in one zone are transmitted into other appropriate zones. One other point of concern should be expressed and that is solutions to the Navier-Stokes codes are dependent on the utilization of turbulence models. Current turbulence models were not derived for the types of flows encountered in this problem. It was expected, therefore, that some solutions particularly those in highly viscous regions will suffer until this need is satisfied.

Increasing fuel prices have caused the aircraft industry to reconsider the utilization of turboprop aircraft. In the paper prepared by H. R. Welge (33), the integration of a prop-fan propulsion system into a transport aircraft is discussed. It was pointed out that a fuel saving of 20 to 40 percent over the current aircraft may be obtained. While the paper indicated that only a small drag penalty occurs for prop-fan integration, it is realized that very limited research has been conducted and that sufficient data to make a reasonable assessment of the flow problems is not available. It is felt, however, that by utilization of the methods currently under development, the propulsion system can be integrated into the aircraft with no interference penalties.

The final area of research covered in this session, as discussed in the paper prepared by R. M. Kulfan and A. Sigalla (35), deals with assessing the methods for predicting the propulsion system interaction effects for a supersonic cruise concept with four podded engines. The development of new threoretical methods is progressing at a fairly significant rate, and as a result the developers must stop and assess these codes on realistic configurations. This approach can be used to guide future research, as well as evaluate concepts under study. The methods utilized in this paper represent the state-of-the-art, illustrating that propulsion interaction effects can be quantitatively predicted. As better (more accurate) approaches are developed, such as a jet exhaust model, these should be added into an overall computational method.

3.0 Round Table Discussion

The symposium concluded with a round table discussion, which focused on the current state-of-the art in each area presented and where the major needs would appear to be:

3.1 Combat Aircraft Intakes

Dr. G. K. Richey summarized the first conference session as follows:

3.1.1 State of the Art

- Performance based on wind tunnel data
- Results flight test verified
- Instantaneous distortion correct appraoch to addressing inlet/engine compatibility
- Emphasis on supersonic speeds ($M \simeq 2.0$)
- Theoretical analysis technique emerging

3.1.2 Potential Intake Design Drivers

- Increased sustained supersonic capability
- Need for expansion of flight envelope
- STOL capability
- Weapons integration
- Reduced detectability

3.1.3 Needs and Opportunities

- Computer/theoretical based intake designs
- Extensions to higher supersonic cruise and maneuver
- Wider range of combat agility/maneuver capability
- Integration with advanced weapons
- Unique configurations
  - Reduced detectability
  - STOL and V/STOL
  - Maneuver freedom

It was pointed out during this discussion that significant progress has been made in the development of computational methods for predicting inlet integration effects. However, there still is a significant amount of research required before an accurate method for predicting flow fields, particularly for inlets placed in unorthodox locations, is available. It was also noted that future activities should focus on investigating the more fundamental physics of the flows, particularly for the flow at the engine face. The need for a consistent criteria for use in determining inlet distortion effects was also expressed.

3.2 Afterbodies and Nozzles

In summarizing the second session of this conference, Mr. Grieb chose to discuss nozzles and afterbodies separately. He summarized this session as follows:

3.2.1 Nozzles for Military Aircraft - State of the Art

- Many designs of convergent and convergent/divergent nozzles utilized on current aircraft
- Extent of variability rather limited
- Marked trend to convergent/divergent nozzles with faired boattails
- Nozzles/thrust reversers currently utilized on only one aircraft

3.2.2 Nozzles for Military Aircraft - Future Development

- 2-D nozzles are in principle, a good starting point for multi-purpose designs with:
  - Fully variable nozzle contours
  - Thrust vectoring
  - Thrust reversing
- Thrust vectoring (vertical and horizontal) attractive with view toward super maneuverability
- Aircraft weight and life cycle cost sensitive to weight and complexity of sophisticated nozzle concepts

Several points should be brought out as a result of this discussion. Current methods for designing nozzles have been based on extensive wind tunnel development programs. Current analytical methods can accurately predict the external and internal performance characteristics for isolated nozzles, however, methods to address the integrated nozzle are just starting to receive the necessary emphasis. As indicated, 2-D nozzles (nonaxisymmetric nozzles) offer the potential for meeting the role required of multi-purpose nozzles. It should also be pointed out that these nozzles which may seem to be sophisticated, may in fact be less complicated than the axisymmetric nozzle used on current aircraft and therefore, offer the potential for a lower life cycle cost.

3.2.3 Afterbodies for Military Aircraft - State of the Art

- Prediction methods for compressible, viscous flow around afterbodies not yet sufficiently developed
  - Influence of jet plume
  - Boundary layer separation
  - Shock/boundary layer interactions
  - Reynolds number influences
- Extensive wind tunnel testing as prime development tool necessary, but limited reliability of results:
  - Wind tunnel calibration problems
  - Reynolds number too low
- Flight tests do not allow identification of afterbody drag

3.2.4 Afterbodies for Military Aircraft - Future Development

- More stringent requirements of aircraft performance and effectivity expected
  - Careful-design of afterbodies with minimum drag mandatory
- Improvement of flow prediction methods important
- Advanced nozzle concepts will cause problems with afterbody aerodynamics, design and engine installation

The major portion of the discussion focused on Reynolds number effects for nozzle/afterbody flows. While no conclusions were drawn, it should be pointed out that to date most all of the carefully constructed wind tunnel tests have indicated that while there was an effect of Reynolds number on the nozzle pressure distribution, there appeared to be no effect on the integrated pressure drag.

3.3 Testing and Analysis Techniques

Mr. Carter summarized the third conference session by dividing it into two separate areas, Military and Civil aircraft. The summary for each was as follows:

3.3.1 Military Aircraft - State of the Art

In general the status is quite promising, but to a large extent is still based on the piecemeal appraoch. Currently techniques for:

- Inlet internal performance, engine face static and dynamic distortion are well established
- Inlet spill drag by force measurements on partial models are satisfactory
- Afterbody performance measurements in the presence of cold or hot jets are not readily available particularly for fully representative military afterbody shapes at incidence
- Through-flow complete model measurements corrected for internal forces are satisfactory but calibration of internal force is often time consuming, expensive and inaccurate
- Complete models with inlet and exhaust simultaneously represented by ejectors or TPS are beginning to be established

3.3.2 Military Aircraft - Current Limitations

- Accurate definition of internal forces
- Afterbody performance measurements, with or without live jet suffer inaccuracy and support interference
- Simultaneous representation of inlet and exhaust flows is difficult, particularly for multi-nozzles

3.3.3 Military Aircraft - Future Development

- Foremost need is for a military simulator providing nozzle pressure ratio and inlet flow
- Even more need for a short simulator for VTOL Pegasus type installations with short inlet/exhaust spacing
- Afterbody performance techniques and development, also associated support systems for minimum interference
- Study needed of inlet/exhaust mutual interference to demonstrate the need or otherwise of simultaneous representation

3.3.4 Civil Aircraft - State of the Art

In general, the position is good. There has been a wide acceptance of the need for high accuracy and correct simultaneous simulation of both inlet and exhaust flows. In general techniques for:

- Inlet internal performance are well established, spill drag measurements are adequate by pressure and force methods
- Single and twin stream exhaust performance measurements are readily available on static rigs and external flow rigs. Hot core flow are also provided.
- For complete and half models simultaneous inlet and exhaust flows with TPS are established, as are direct twin stream exhaust blow methods. Use of ejection is still developing. This work is essentially confined to large wind tunnels, current TPS sizes are dictating model scales.
- Calibration of simulators is developing and is probably defining the present accuracy limits.

3.3.5 Civil Aircraft - Current Limitations

- The model performance techniques being developed for both half and full models are very expensive and somewhat inflexible
- There is not adequate digested information at present to demonstrate the consistency and repeatibility of simulators
- Present performance measurements on inlets are invariably isolated. Representation of the curved environment flow due to wing is rarely simulated.
- Present performance measurements on exhaust nozzles are usually isolated but should be made in the presence of the wing, this is possible for discharge coefficients but very difficult for thrust.

3.3.6 Civil Aircraft - Future Development

- Consolidation of current techniques
- Examination of data from simple through-flow representation in comparison with exhaust simulators to optimize through-flow builds
- Validation of the half model vs full model techniques and possible tunnel interference with exhaust flows
- Development of model support systems for 3 engine and rear engine configurations forward blade support interference development
- There is virtually no information on Reynolds number effects on installation performance
- Consideration must be given to engine representation in cryogenic facilities. Ejector or blown nacelles may have advantages of representing correct temperature ratios.
- Propellers, before they become reality, the main principles of mutual propeller/wing interference should be considered, as must be the bookkeeping

The major question brought out in this session deals with the use of simulators to provide the proper inlet and exhaust flow simulation for experimental testing. These types of simulators have been used predominately in civil aircraft research, but have not, because of the separation of the inlet and exhaust systems, been utilized in research on military aircraft. If, however, the engines for future military aircraft are placed in podded arrangements, typical of V/STOL aircraft, where the inlet and exhaust systems are fairly close together, flow simulators may be required. Before committing to this added complexity, there is a need to assess in an experimental program the interactions and accuracies associated with simulating the required flows. For transport aircraft, where the inlet and exhaust nozzles are close together, proper flow simulation is definitely required where a high accuracy is necessary. All of the methods currently used do not completely simulate all the flows required along with the exact model geometry. Increased research activity is required to fully assess the need for simulators and to provide a proper simulation without having to incur such a high level of complexity.

3.4 Installation Aerodynamics of Transport Aircraft

The fourth session of the conference was summarized by M. Leynaert. The primary question that he considered, was "How to minimize the installed drag for transport aircraft." The solution to this problem can be based upon the following three elements:

- Theoretical calculation methods for design/off design conditions
- Experimental wind tunnel studies
- Use of existing results, as a preliminary guide

The speaker indicated that considerable progress has been made in the development of computational methods for predicting the propulsion interaction effects. However, there are many areas which require improvements. Such as:

- For transonic potential flow calculations
  - Improvements in the resolution of the equations
  - Couple with twin nozzle flow calculations
  - Couple with viscous effects
- For viscous flow calculations
  - Include 3-D laminar separation and transition
  - Include 3-D shock boundary layer interactions
  - Include shear layers

In every theoretical development program very detailed, high quality experimental data is required for use in verifying these new codes. The experimental data which will be supporting the computational developments fall into the following categories:

- Isolated Nacelle
  - Inlet and exhaust nozzle designs
  - Detailed flow and performance characteristics
- Installation Effects
  - Optimization of overall configurations
  - Improvements in localized areas

4.0 Conclusions and Recommendations

Based on the results of the presented papers and the round table discussion, the following conclusions and recommendations can be made:

1. The development of computational methods is a key area of research for the development of future aircraft concepts. Current methods are somewhat limited in nature, and research in this area should be expanded as rapidly as possible. The primary areas which need consideration and increased emphasis are the inclusion of strong viscous interaction and the development of more realistic turbulence models. The development of adequate turbulence models is the key to future development of codes based on the use of the Navier-Stokes equations.

2. With the development of more complex and rigorous methods there is a need to concentrate research on methods which can be used to increase the computational efficiency. The computational time currently required to solve problems using some of these advanced codes is prohibitive, and while some methods to reduce computational time are under study, such as multigrid or embedded grids, there is a need to expand this research.

If these newly developed codes are to be widely used throughout the aeronautical industry, particularly during preliminary design cycles, they must be user oriented. That is, all of the complex functions usually accomplished by the user will have to be done by the computer. In addition, research in this area will also require a concentrated effort on the development of geometry packages which can handle the complex shapes usually encoutered on modern day aircraft.

3. A very vital part of any advanced theoretical methods development program is the need to have very detailed, high quality experimental data to use in verifying these new methods. Experimental programs which are carefully planned and oriented to satisfying this need must be considered as an integral part of any theory program.

4. In the past, propulsion simulation testing has been conducted only after the external lines of the aircraft are frozen. This approach usually results in the aircraft having higher drag than specified. If this type of testing is conducted early enough in a design cycle, these problems can be avoided. It is suggested that every effort be concentrated on obtaining the necessary data early enough, so as to avoid these problems.

5. Propulsion simulators (simulating both inlet and exhaust flows simultaneously) have been used in civil transport testing for a number of years. There has been little effort in extending this capability into wind tunnel testing on fighter aircraft concepts. It is felt that research should be expanded that will identify whether the propulsion simulators are needed for model scale of military aircraft testing and to develop simulators which are reliable and give repeatable results.

6. There is a need to alter current conventional thinking and concentrate on unconventional aircraft concepts or aircraft components which have the potential for significantly increasing performance capability, reduce weight, reduce cost or reduce detectability. The concepts which should be given consideration are unconventional location and shapes of inlet and exhaust systems, the utilization of the propulsion system to provide STOL capability, increased maneuvering and control forces; alternate propulsion system locations for subsonic transports and high speed propfans.

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14. Abstract

The AGARD Fluid Dynamics Panel held its Spring Symposium 1981 on the "Aerodynamics of Power Plant Installation" at Toulouse, France, 11–14 May 1981. The theme of the Symposium was:

– Powerplant installations involve complex flows, strongly influenced by viscous effects and often with important aerodynamic interactions between the airframe and propulsion system. The introduction of new vehicle propulsion concepts, and new points of emphasis in aircraft and missile design requirements, provide an expanding range of aerodynamic problems which call for both experimental and theoretical study. It is the purpose of the symposium to survey the current and foreseeable aerodynamic problems in powerplant installation and to review recent work which has improved basic understanding or has enhanced prediction and design methods in this field.

Four sessions were held – combat aircraft intakes, afterbodies and nozzles, testing and analysis techniques, and installation aerodynamics of transport aircraft.

This Technical Evaluation Report includes an evaluation of the state of the art and recommendations for future work in the subject area.

This Advisory Report was produced at the request of the Fluid Dynamics Panel of AGARD.

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